Progress Report on the Laser Absorption Spectrometer Development

Gary D. Spiers, Robert T. Menzies
Jet Propulsion Laboratory
Pasadena CA 91109
Email: gary.spiers@jpl.nasa.gov

Mark W. Phillips, James Ranson
Coherent Technologies Inc
Lafayette CO 80027

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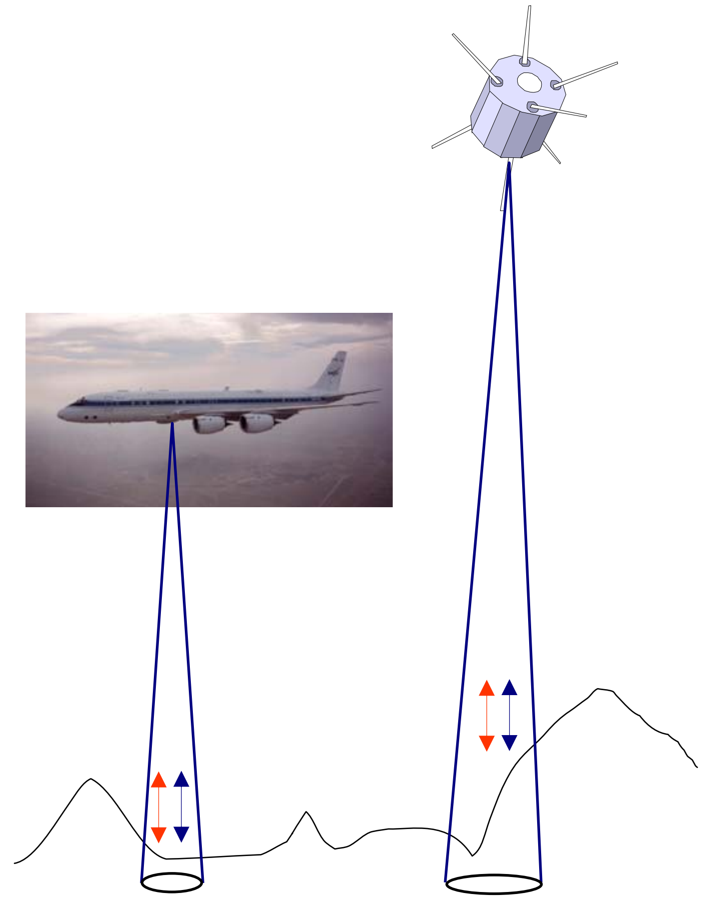
Presentation Outline

- What is the Laser Absorption Spectrometer (LAS)?
- Why Coherent LAS? – Pro’s and Con’s
- Airborne LAS Transceiver Architecture
  - Higher power METEOR lasers
  - Frequency Offset-Locking
  - Absolute Frequency Locking to CO_2 Cell
  - Mechanical Overview
  - Telescope Design
- Impact of Measurement from Aircraft
  - Need for dynamically tuned receiver frequency band
- Activities for next year

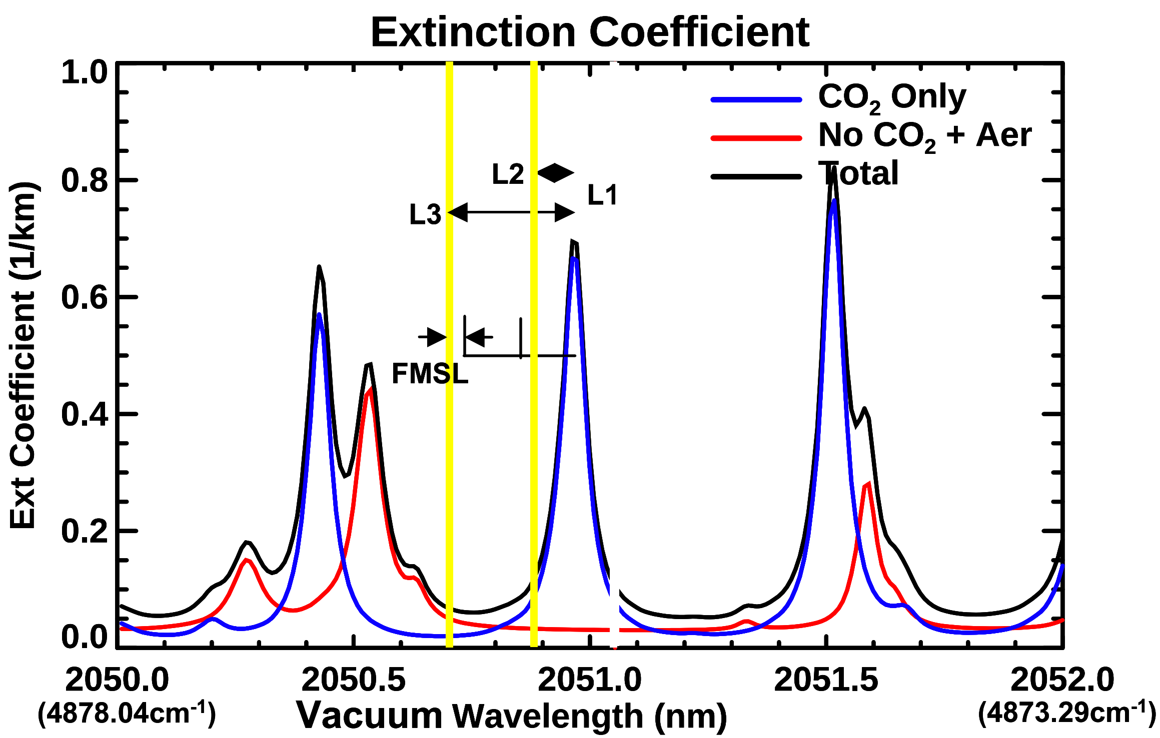
Concept for Global CO_2 Laser Absorption Spectrometer (LAS)

- Transmit and receive near nadir-pointing laser beams with on and off-line wavelength channels
  - Ground surface reflection (land and sea) provides return signal – requires co-aligned beams to obtain equal backscatter coefficients and equal depolarization factors for both channels
  - Measure difference in integrated path absorption at these two wavelengths
- Use additional sensor data (temperature, surface pressure, altimetry) to extract value of CO_2 concentration
  - Goal of 1 ppmv precision with ~ 50-100 km horizontal resolution (large scale measurements)
- Eventual plan is to perform global measurement from Low Earth Orbit Satellite (LEOS) platform
- Development plan includes interim measurement and technology demonstration from airborne platform – NASA DC-8 Science Aircraft



Key Design Features of the LAS Transceiver

- Coherent CW transceiver with 3 lasers and two broadcast channels
  - Laser 1 locked to center of CO_2 line feature at 2051nm for absolute frequency reference
    - Line selected for low temperature dependence of absorption strength and for match to emission wavelength of Tm,Ho:YLF laser
  - Laser 2 offset-locked by 4GHz to Laser 1 for broadcast on side of absorption feature
  - Laser 3 offset-locked by 20GHz to Laser 1 (FM sideband lock) for off-line broadcast

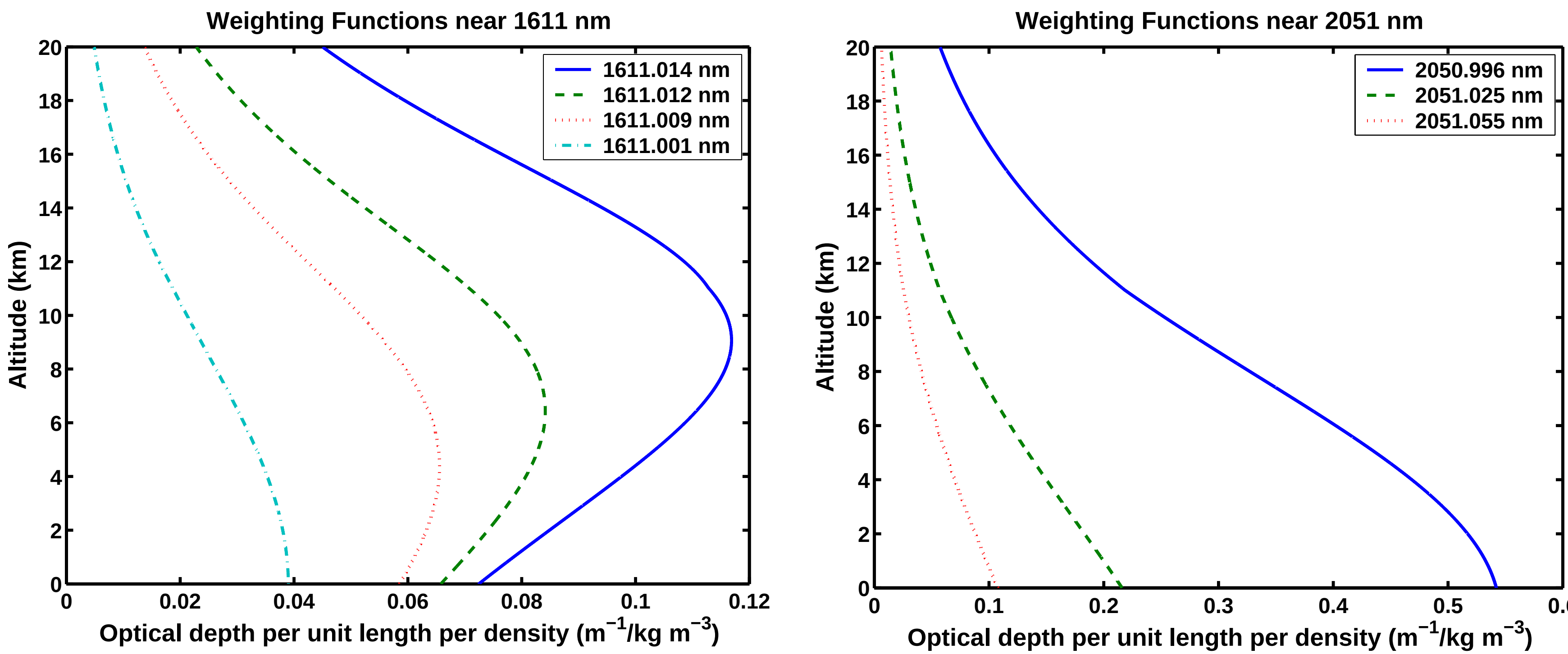


Line center at 2050.96nm vacuum wavelength ($4875.749 cm^{-1}$)

Offset-locked lasers tunable by +/- 4GHz about set-point

FM sideband frequency spacing ~9GHz for relative off-line offset of ~2GHz

LAS Weighting Functions provide Altitude Resolution

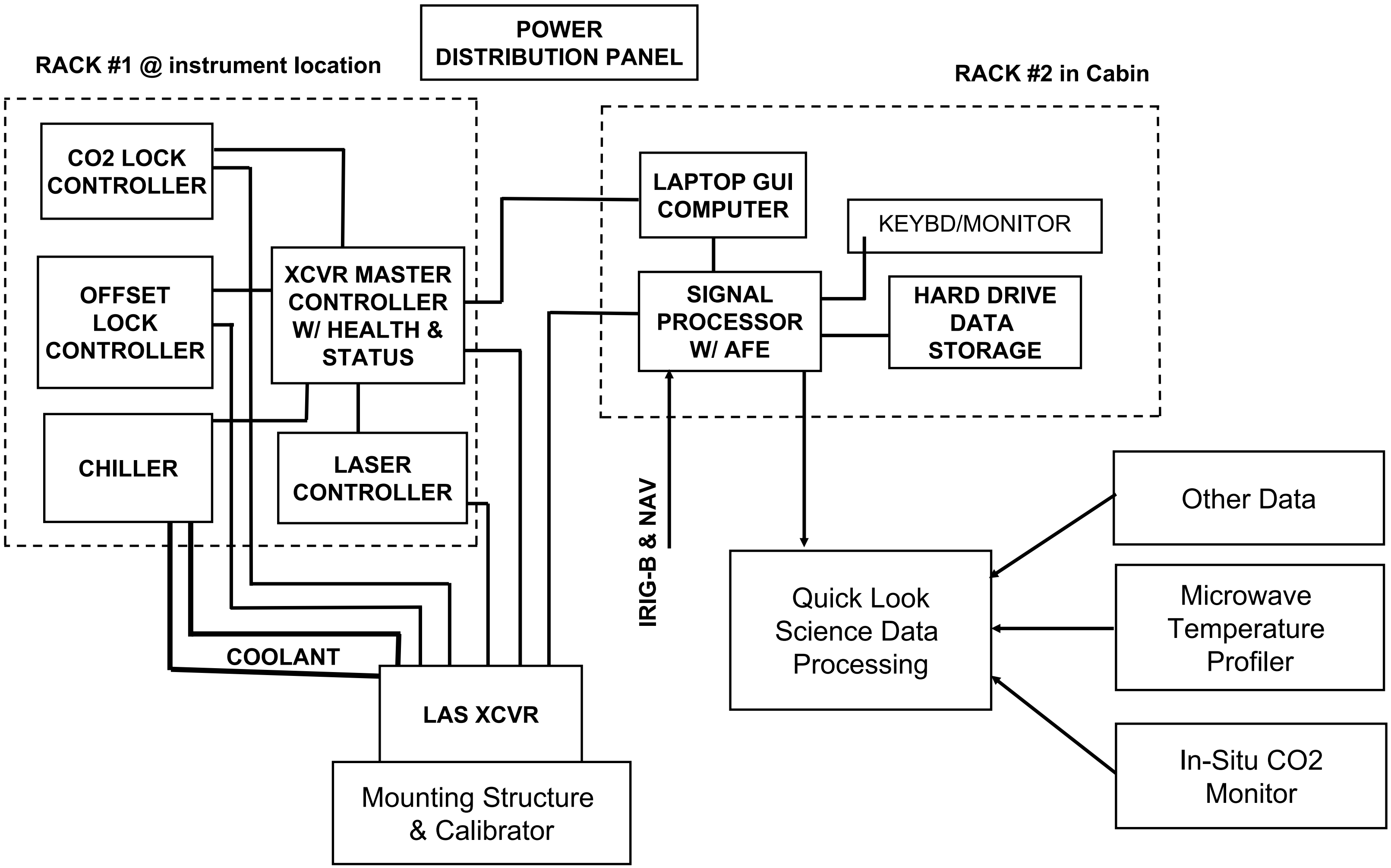


- LAS at 2050.9nm biased to PBL (<2km from surface) where CO_2 source and sink structures are most measurable against 370 ppmv background
- Strong bias to PBL allows a single on-line wavelength to be used in the LAS measurement without ambiguity

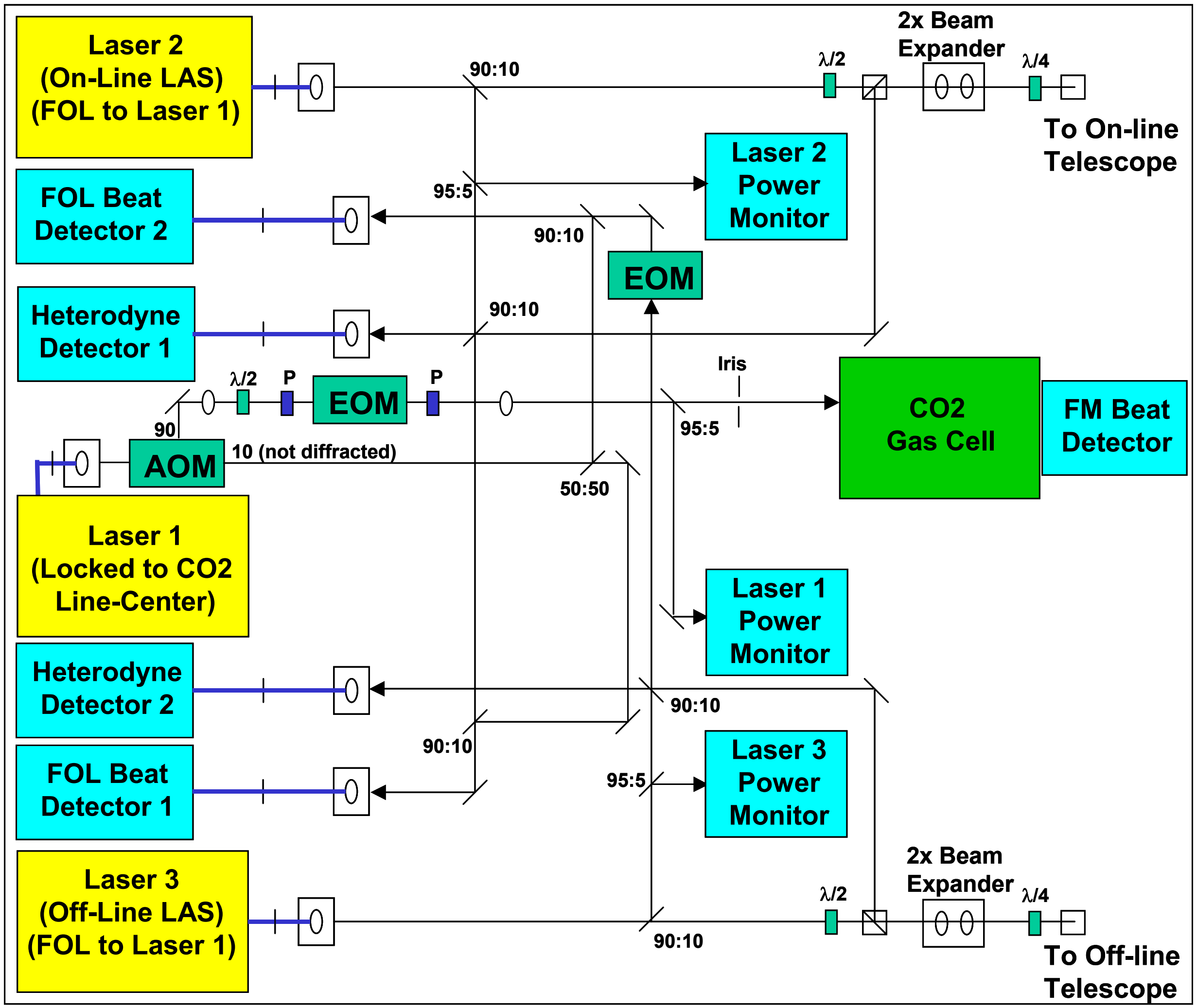
Why Coherent LAS? Pro's and Con's

- Pro's:
  - Coherent detection CW LAS offers improved narrowband SNR for a given transmit power and aperture size compared with direct detection with a pulsed transmitter
    - Narrow-band heterodyne detection reduces detector Noise Equivalent Power (NEP) and sensitivity to background irradiance
  - Attractive especially for space-borne measurement due to reduction in Power-Aperture product (with associated reduction in instrument complexity and launch cost)
- Con's:
  - Statistical distribution of intensity in speckles (coherent detection) results in a relative uncertainty in estimate of mean value ~ proportional to $N^{-1/2}$, where N is number of independent samples (speckle realizations)
  - For 0.1% measurement precision (0.4 ppmv precision in 370 ppmv level), require averaging over 1 million independent speckle realizations
    - With a 4cm transmit beam radius, 1M samples = 40km measurement resolution
    - At 200m/s flight speed, each LAS measurement obtained every 200 seconds
  - Equivalent values for space-based platform:
    - 12cm transmit beam radius (30cm aperture), 1M samples = 120km resolution
    - 7km/s orbit velocity, each LAS measurement obtained every 17 seconds

LAS System Diagram

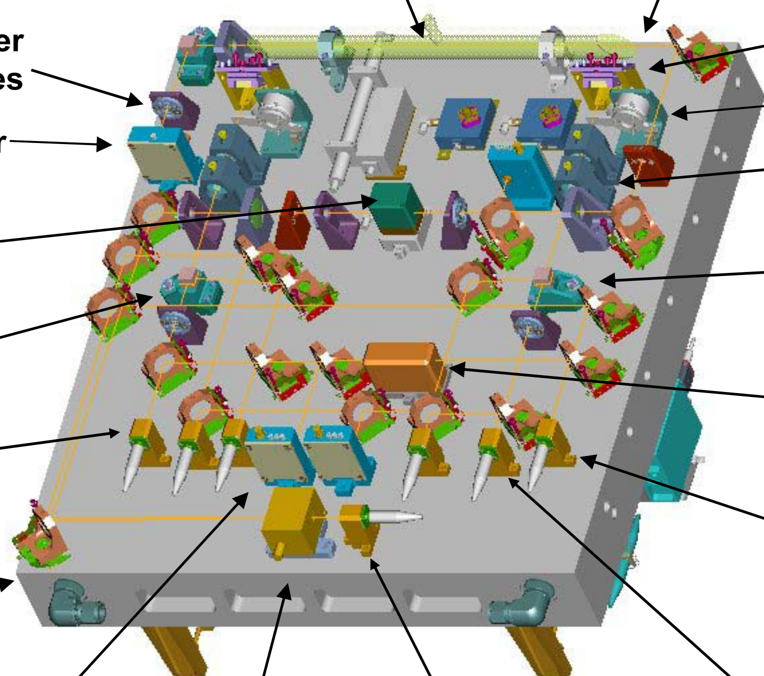


Functional Configuration of LAS Transceiver Optical Bench (Surface 1)

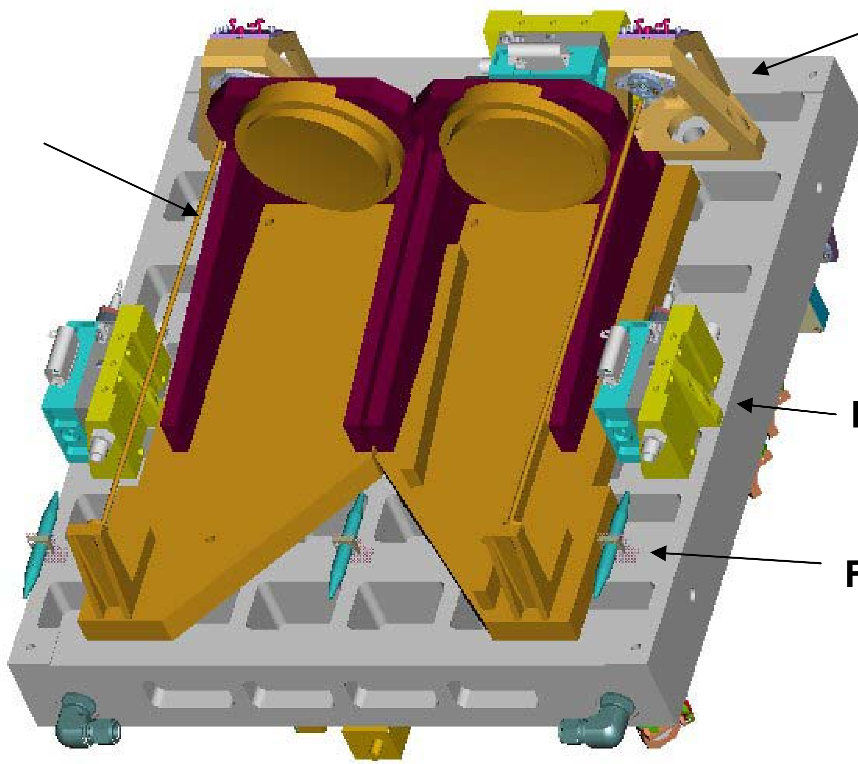


- Dual monostatic layout (on-line and off-line) using PM spectrometer for CO_2 lock
- Lasers and ¼ wave plates physically located on Surface 2
- JPL providing on-board reference target for calibration check of on-line and off-line channels during flight
  - Allows correction for component thermal sensitivity, required for amplitude measurements with 0.1% precision

Optical Bench Layout - Surface 1 with Reference CO_2 Cell

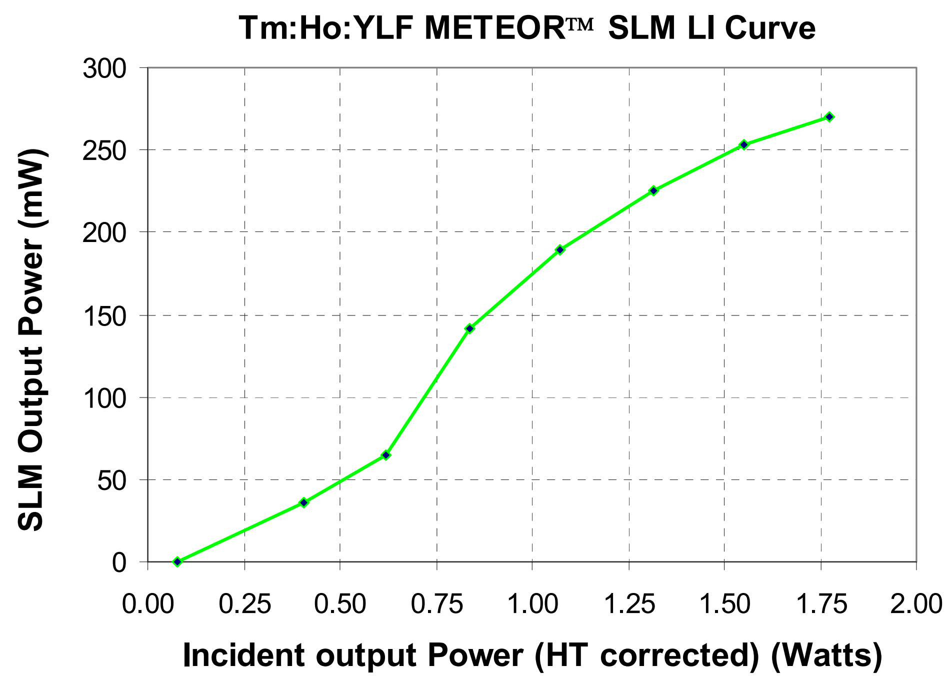


Optical Bench Layout – Second Surface with Telescopes and fiber-coupled Lasers



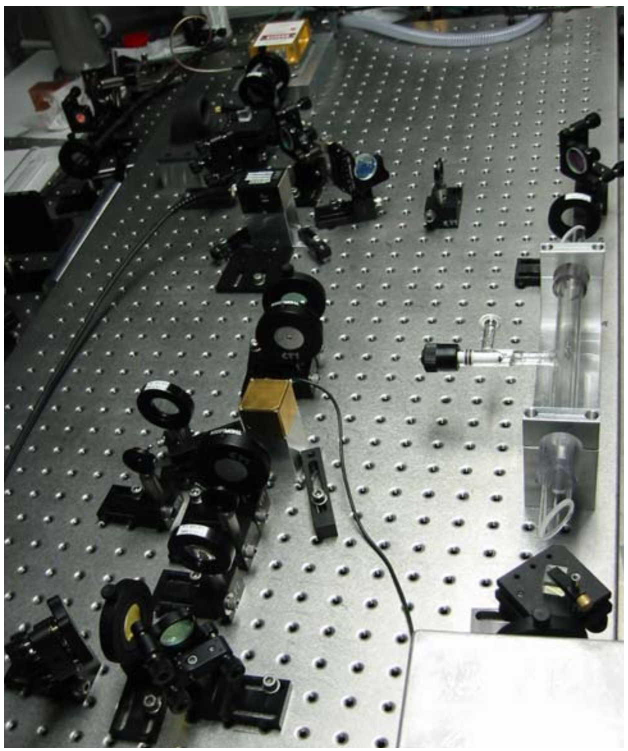
Higher Power Tm,Ho:YLF Laser developed for CO_2 LAS

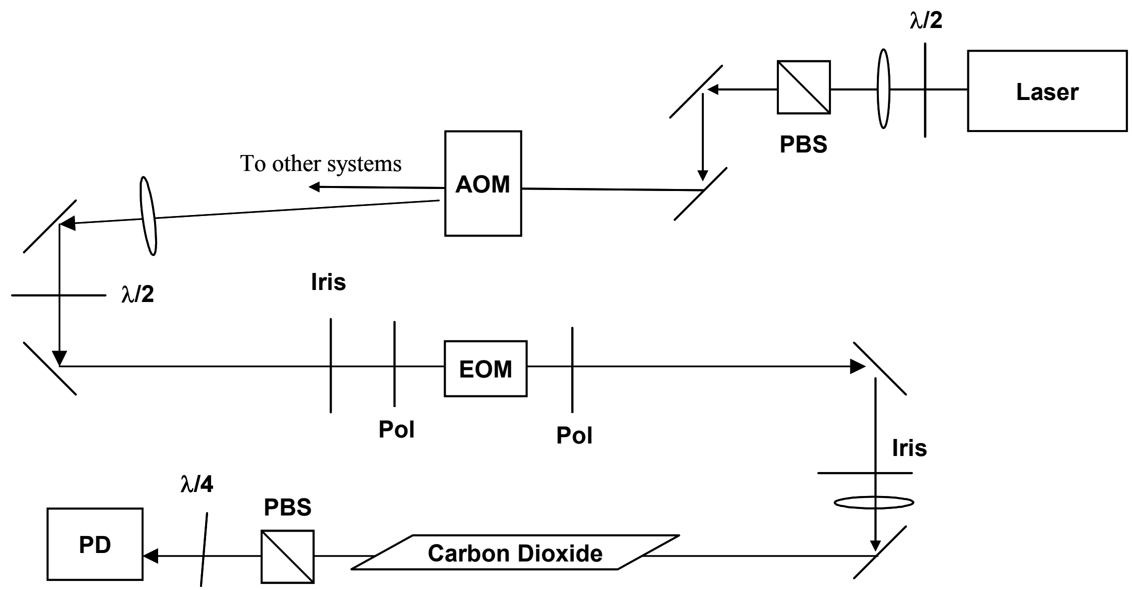
- 250mW Tm,Ho:YLF METEOR® developed using 3W pump diode
  - 150mW output to LAS telescopes (including fiber-coupling loss)
- All frequency characteristics same as standard CTI 50mW METEOR®
  - 5-10kHz/ms linewidth, free-running
  - All units in LAS XCVR PZT-tuned for absolute and relative frequency lock



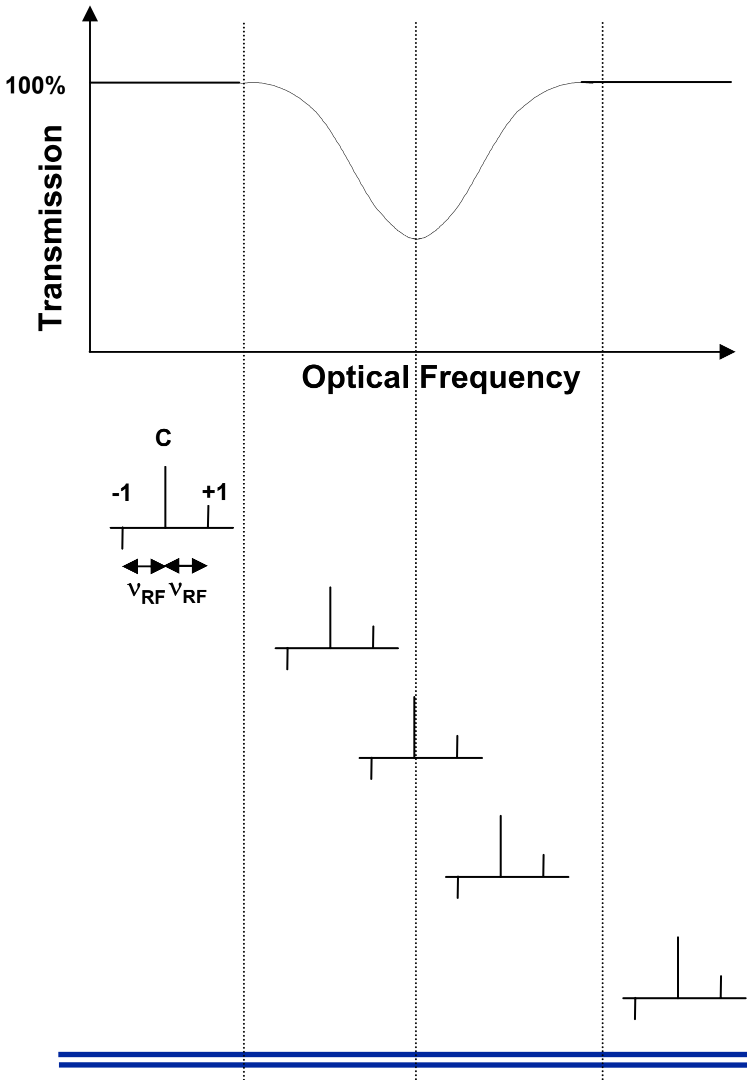
Absolute Frequency Lock to Reference CO_2 Cell

- Phase Modulation (PM) Spectrometry used to lock Laser 1 (reference laser) to CO_2 line center at 2051nm
  - EOM provides FM sidebands at +/-170MHz for probing Doppler-broadened line profile (~350MHz linewidth at 0.5 Torr) – high error signal slope at lock point
  - AOM isolates CO_2 lock optics from "unwitting interferometers" arising from rest of system optics – Residual Amplitude Modulation (RAM) noise reduction
  - Other optics (lenses, polarizers, iris) also introduced to reduce RAM noise



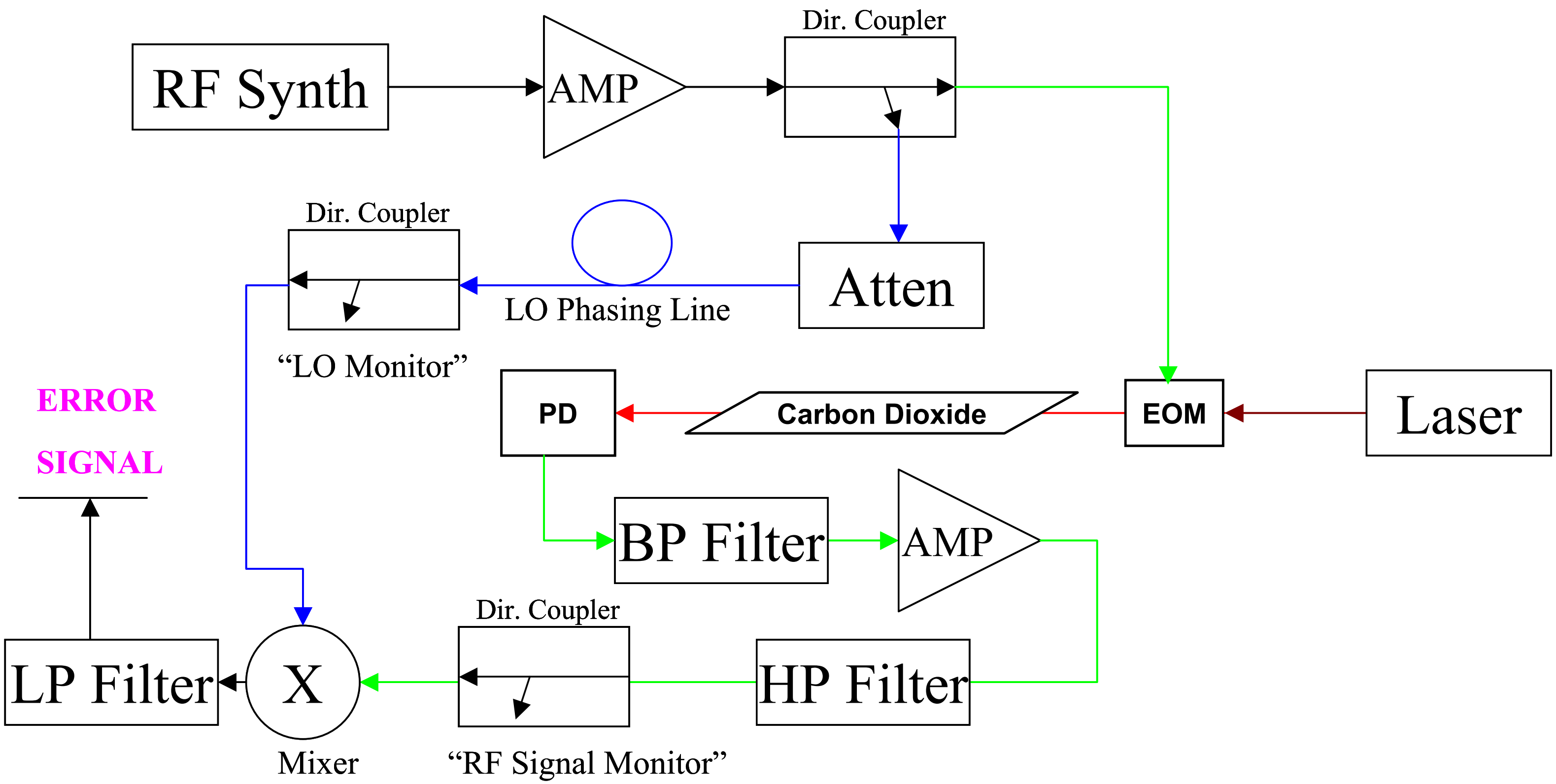


Error Signal Generation using Phase Modulation Spectrometer



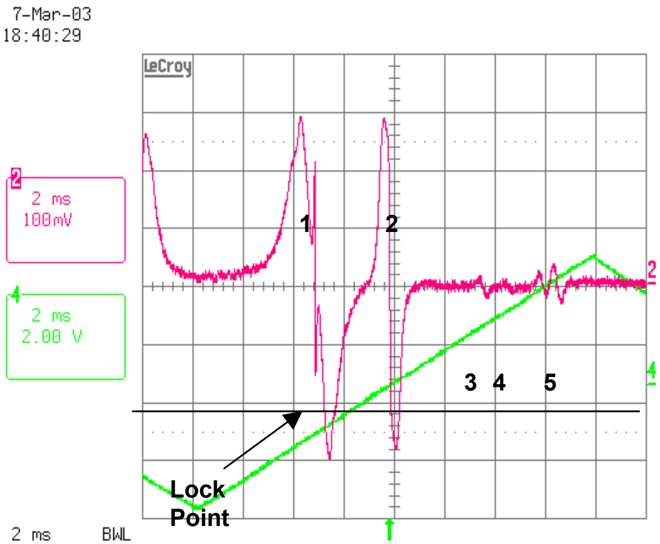
- Electro-optic modulator imposes equal amplitude and opposite phase sidebands on the carrier (C)
- Spectrometer detector measures the added beat amplitudes of the two sidebands with the carrier
- Away from the absorption feature, both sidebands are transmitted equally (100%)
  - The combined error signal is zero
- At line center, both sidebands are equally attenuated (straddling the symmetric absorption feature)
  - The combined error signal is again zero
- On either side of the absorption line center, one sideband is attenuated less than the other, resulting in a non-zero error signal with reversed polarity about line center
  - Error signal used in servo loop to tune carrier frequency to absorption line center

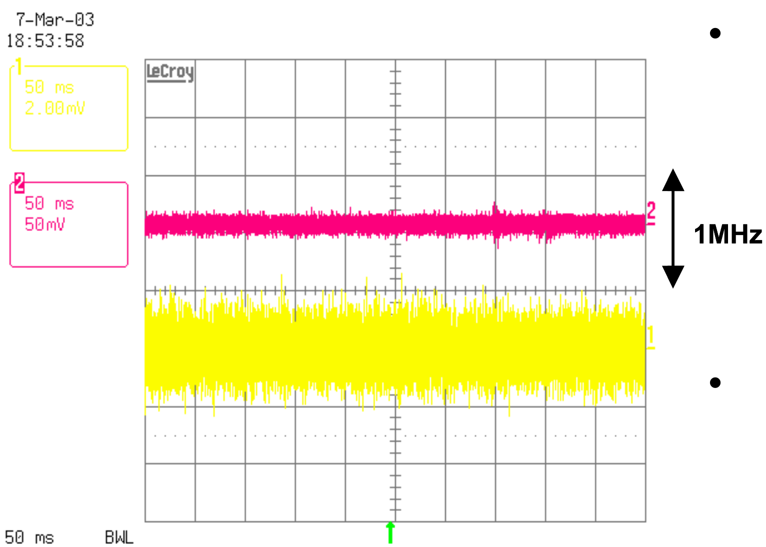
Phase Modulation Spectrometer Electronics Design



- RF detection phase depends on path difference of LO signal (blue) and modulation signal (green), including optical path from modulator to detector (red)

Survey Scan and Absolute Lock to Reference CO_2 Cell

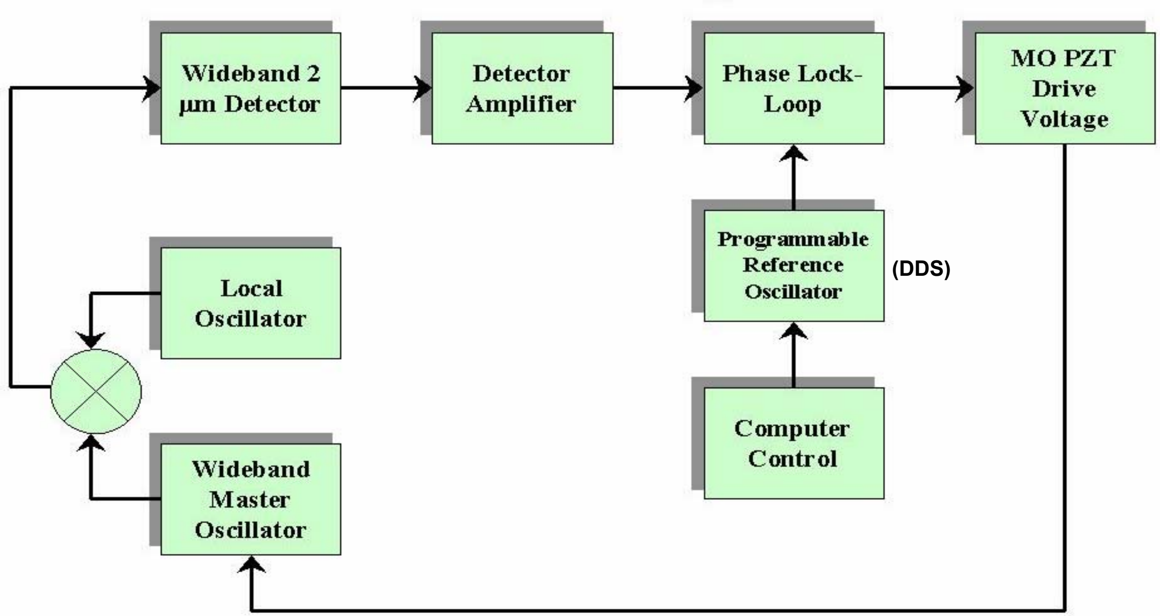




- Upper plot shows a survey scan over 20 GHz tuning range of METEOR® laser
  - Red trace shows output of PM spectrometer (CO_2 lock error signal)
  - Green trace shows laser PZT voltage
- 5 peaks identified (CO_2 isotopes)
  - Peaks #1 and #2 distorted because of high amplitude (RF amplifier saturation)
  - Instrument is locked to strongest peak, #1 at ~2051nm (4875.749cm^{-1})
- Locked laser shows peak-to-peak frequency excursions of less than 300kHz
  - Major improvement over previously reported performance for absolute frequency lock to CO_2
  - Red trace is demodulated error signal
  - Yellow trace is raw RF beat signal
- CO_2 LAS measurement requires absolute frequency knowledge to <1MHz (long-term linewidth, not peak-to-peak variation)
  - Absolute frequency lock readily achieved

Offset Locking of Online and Offline Lasers

- Frequency Offset-Locking hardware is used to locate on-line and off-line laser frequencies w.r.t. line-center reference laser frequency
  - Typical offset-locking accuracy previously demonstrated ~ 5kHz
  - Frequency noise of locked laser matches that of reference laser for noise components inside servo bandwidth
  - Additional high frequency noise of locked laser similar to that of reference laser
  - As a result, locked laser has ~ same short-term linewidth as reference laser (5-10kHz/ms)



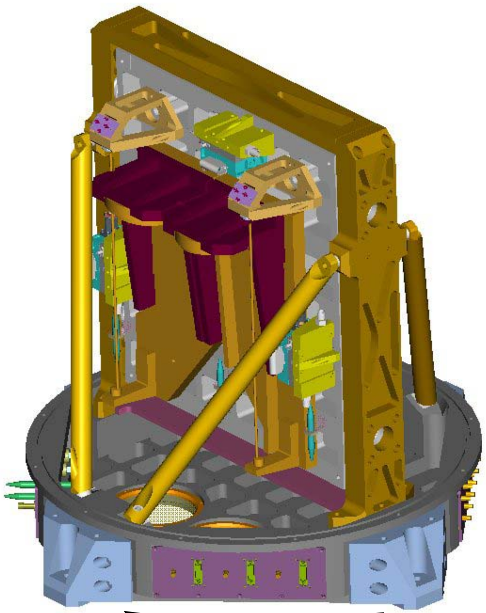
- Offset-Locking Process:
  - Output from Tunable Laser (MO) and Reference Laser (LO) optically mixed and detected with wideband photodiode/ preamplifier package
  - Beat frequency compared with preset frequency generated by Direct Digital Synthesizer (DDS)
  - Phase-locked loop error signal amplified and used to drive MO frequency actuator (PZT)
  - Zero-crossing error signal obtained when beat frequency matches DDS frequency

Support and Vibration Isolation System

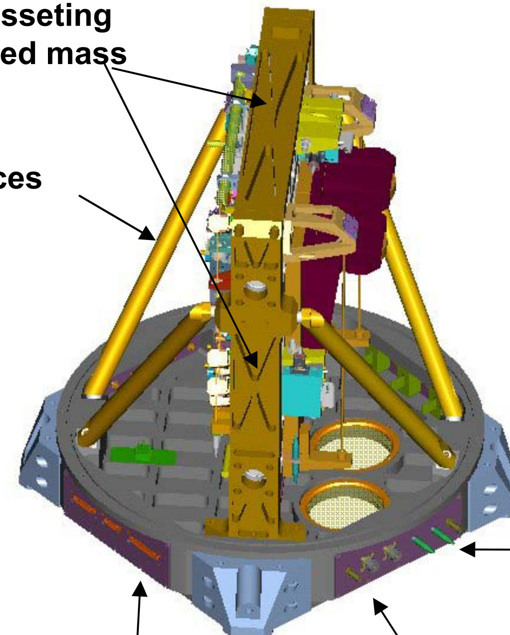
Frame structure w/crossed gusseting provides high stiffness, reduced mass

1-1/4" OD Alum. 6061-T6 Braces

Four connector panels to accommodate feedthrus



Base Structure



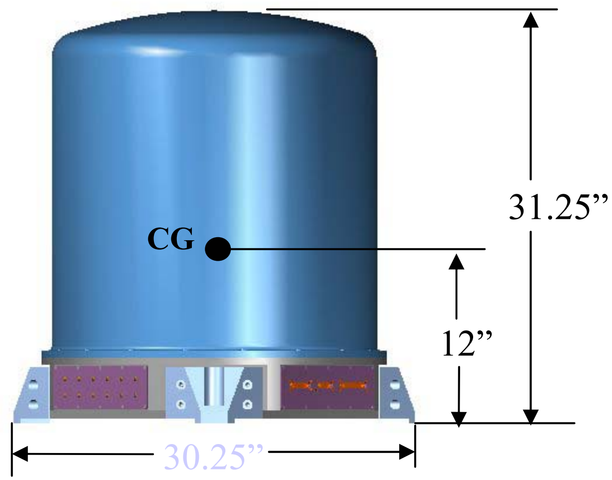
Fiber and liquid feedthrus

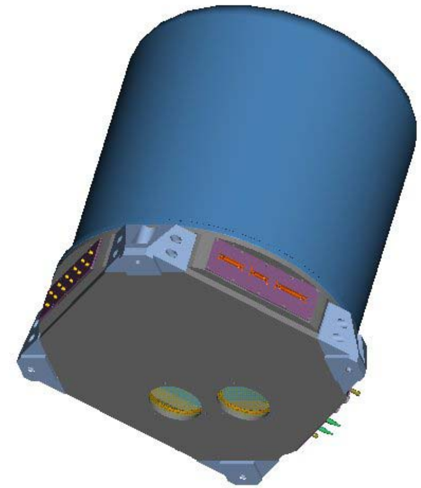
Valves for purging w/dry nitrogen (LN_2 boil off)

Hermetic D-Sub connectors

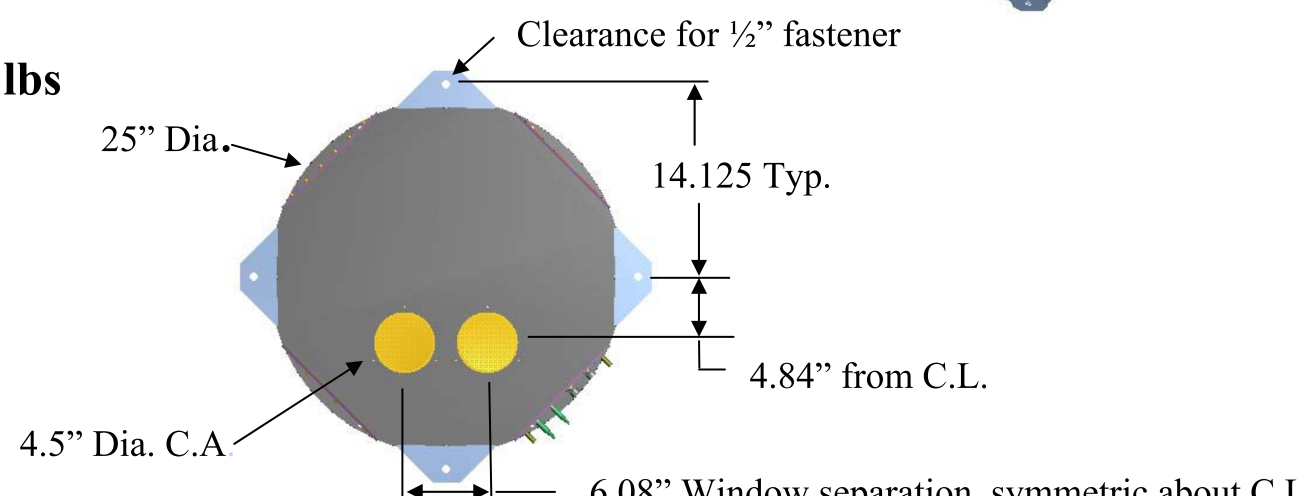
Four point mounting to support structure implemented at critical locations

Enclosure Design

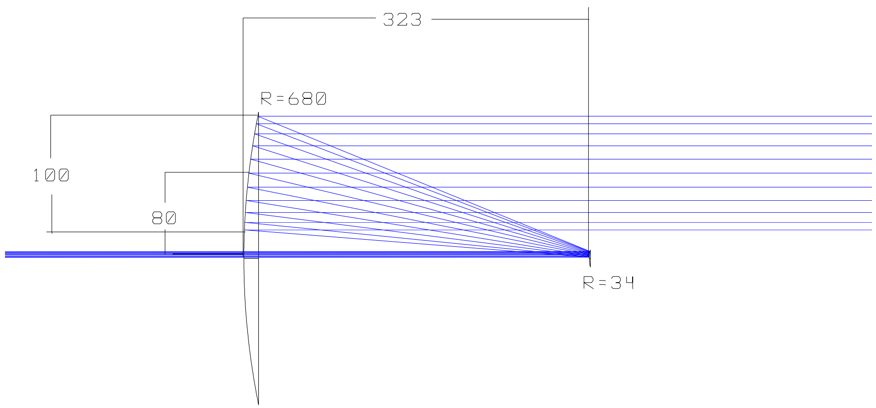


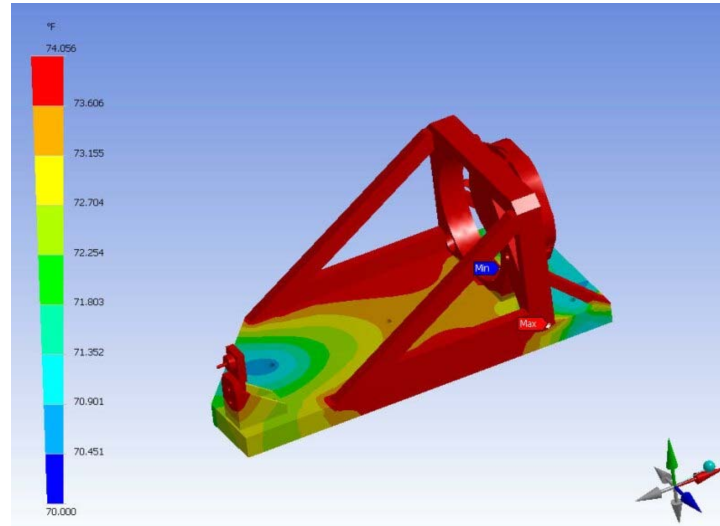


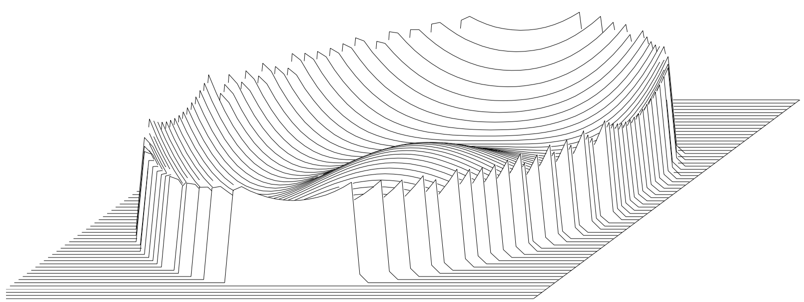
Estimated Mass: 280 lbs



Telescope Design and Analysis







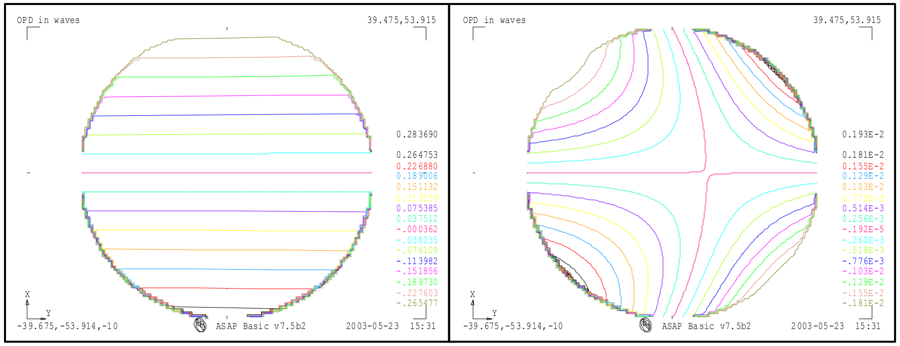
Peak to valley 0.034 waves @ 2 microns

Table 2. Tolerance budget requirements

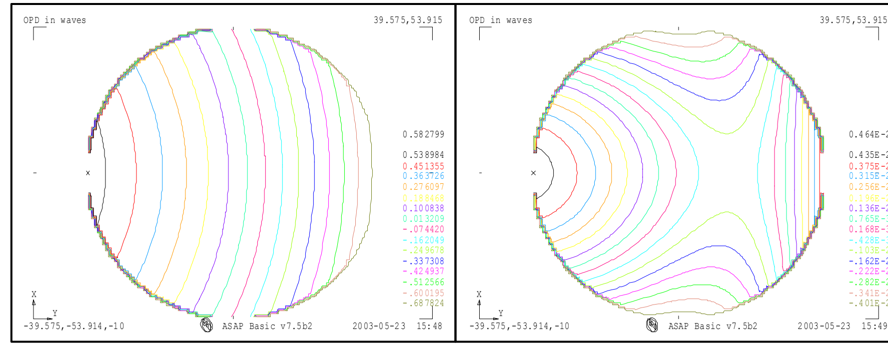
	Parameter	Tolerance	Resolution of adjustment	Range of adjustment	Temporal stability
Telescope alignments	Lateral positioning of the secondary mirror	+/- 0.05 mm.	0.005 mm	+/- 0.5 mm.	+/- 0.007mm.
	Axial positioning of the secondary mirror	+/- 0.05	0.005 mm	+/- 0.5 mm.	+/- 0.03 mm.
	Angular positioning of the secondary mirror	+/- 0.5 mrad	0.01 mrad	+/- 10 mrad	+/- 0.025 mrad
Telescope to board alignment	Angular positioning of the telescops	+/- 0.1 mrad	0.07 mrad	+/- 2 mrad	+/- 0.02 mrad
Periscope alignments	Angular positioning of the illuminating beam	+/- 0.5 mrad	0.05 mrad	+/- 10 mrad	+/- 0.1 mrad
	Lateral positioning of the illuminating beam	+/- 0.2 mm.	0.1 mm.	+/-5 mm.	+/- 0.1 mm.

Telescope Design and Analysis

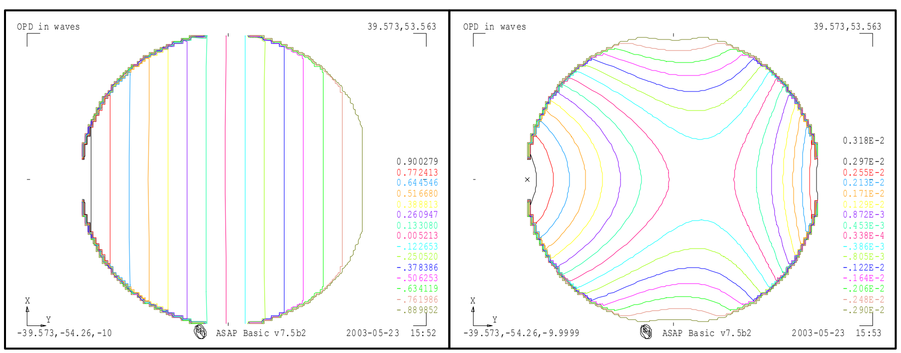
Secondary mirror lateral displacement



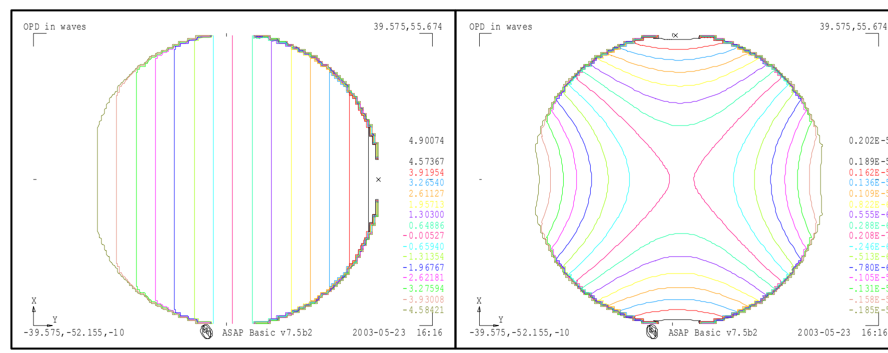
Secondary mirror axial displacement



Secondary mirror tilt



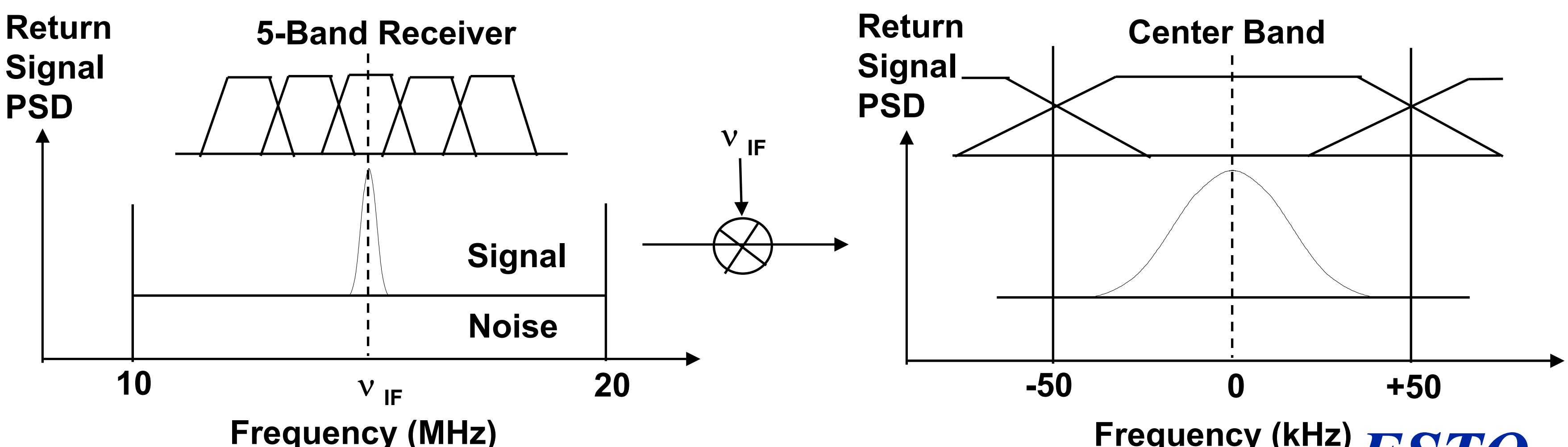
Input beam tilt



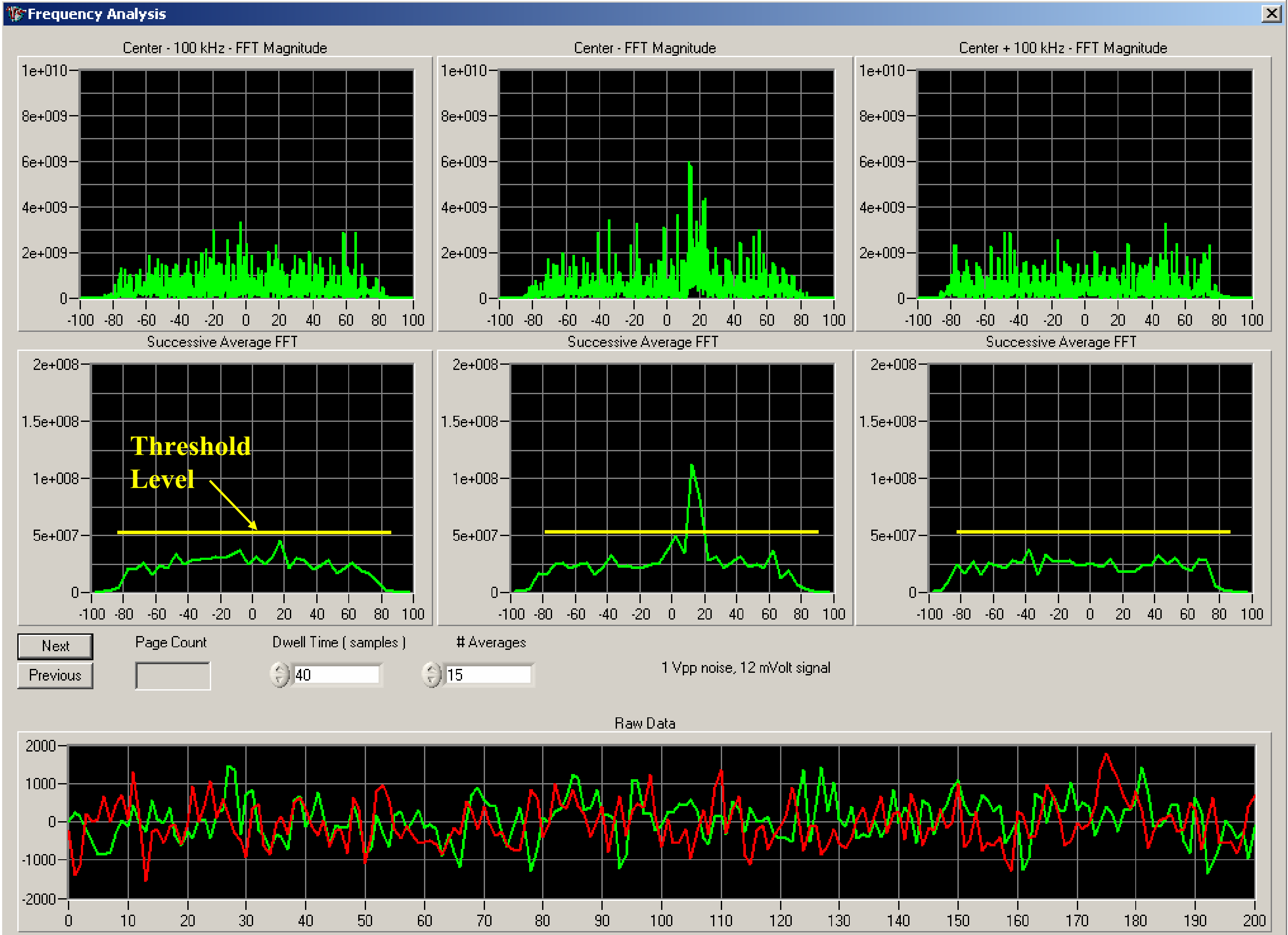
Dominant output wavefront error is tilt, which does not matter, all others are < $8.9 \times 10^{-3}\ \lambda$

LAS Bandwidth Reduction increases CNR and reduces Data Storage

- Instrument attitude adjusted for LOS Doppler frequency shifts centered at 15MHz (with ~+/- 1MHz variation due to expected aircraft and target motion)
  - Front-end receiver band set to 10 to 20MHz
- Digitally tunable 5-band filter used in signal processor (both for on-line and off-line channels) to determine and center Doppler-shifted return signal
  - Maximum amplitude algorithm and in-band FFT's used to center return signals within center detection bands (using stronger off-line channel signal for tuning control)
  - 10 bands digitized (5 for on-line, 5 for off-line) for signal capture and centering
  - 6 bands (3 on-line and 3 off-line) mixed to base-band and stored (I and Q) for post processing
  - Front end digital tuning adjusted every 1ms, initialized using Aircraft INS data
  - Narrowband SNR (CNR) increased due to bandwidth reduction per bin from 10MHz to 100kHz



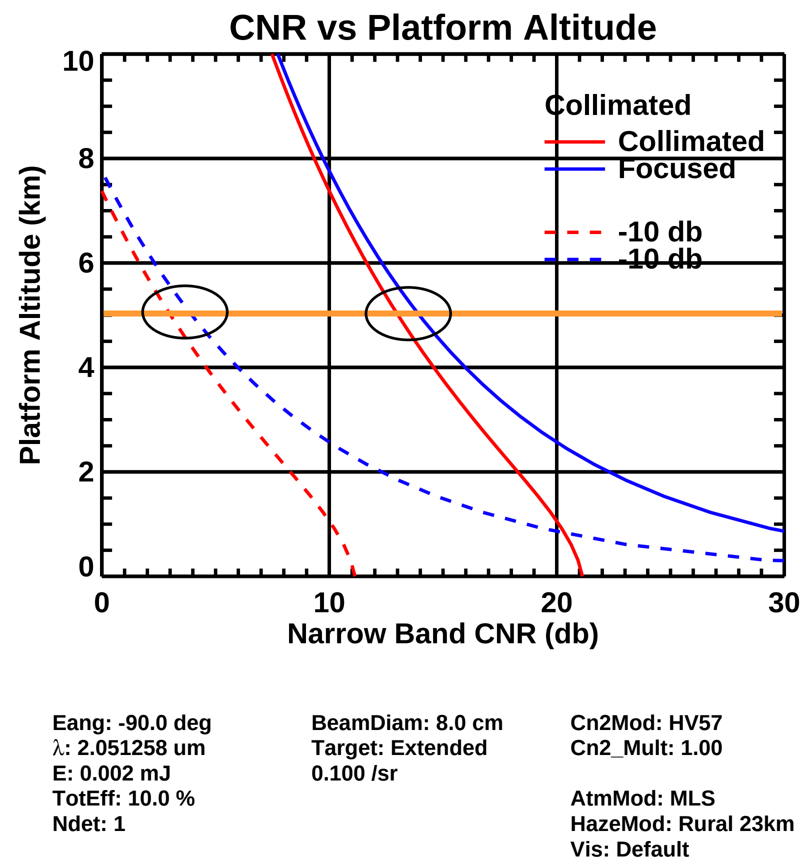
Digitizer able to track and center signal at -3dB CNR (integrated power)



Digitizer Tracking Performance at -6dB CNR (integrated power)

Expected off-line CNR allows robust ground return frequency tracking

- Assumptions for plotted data
  - 8cm beam diameter, monostatic
    - Effective beam diameter will be reduced due to aircraft boundary layer, especially towards rear of aircraft – degradation in CNR
  - 10% lidar system efficiency
  - Off-line LAS wavelength 2051.25nm
  - ρ_π = 0.1 and 0.01 /sr
  - Good visibility
- For 100kHz processor bandwidth and 5km platform altitude:
  - Off-line CNR ~3dB for 0.01/sr reflectance
    - Acceptable for tracking algorithm
  - Off-line CNR ~13dB for 0.1/sr reflectance
    - Tracking algorithm should be robust while allowing for CNR reduction due to aircraft boundary layer



Presentation Summary

- LAS Transceiver being developed for Integrated Path Differential Absorption (IPDA) CO_2 concentration measurements from NASA DC-8 aircraft
  - System Level CDR recently completed (May 2003)
  - Telescope integration and ground tests to be performed beginning of 2004
  - Flight measurements due late 2004
- Design based on previous CTI sub-assemblies for airborne sensors
- Required laser performance demonstrated in 1st of 4 identical units
  - Fabrication of remaining 3 units nearly completed
- Absolute frequency locking demonstrated to required sub-MHz accuracy
  - CO_2 lock obtained to Doppler-broadened line (~350MHz wide) using PM Spectrometer technique with sidebands at +/- 170MHz
- Offset-locking requirements identical to previously demonstrated performance
- Dynamic tuning of receiver bandwidth required to correct for aircraft motion
  - Risk reduction demonstration indicates function may be performed with COTS digital front end unit